Call For White Papers On Research Opportunities In Inertial Fusion Energy

TITLE:

Kilojoule, nanosecond testbed development and operation for 2-omega laser-plasma interaction using novel targetry.

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TOPICS:

- Target physics and design
- Targets (including manufacture, injection, and survivability)
- Drivers (including driver-specific technologies, e.g., final optics)
- LPI experiments

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EXECUTIVE SUMMARY:

Any future installation for inertial fusion energy (IFE) will have to cope with issues related to high repetition-rate: targetry, debris, alignment, electromagnetic pulses (EMP), chamber activation, data management, etc.
The P3 infrastructure of the experimental hall E3 of ELI-Beamlines Center (operated by Department 89) accommodates a high repetition-rate kilojoule, nanosecond beamline (L4n, see Fig. 1 [9]), designed to investigate three major topics of relevance to direct-drive ICF:

- laser-plasma interaction in the sub-critical corona (laser absorption, beam smoothing, parametric instabilities, hot electron generation etc.) at the wavelength of 527 nm, which is of interest for the high-gain ICF reactor design
- measurements of equation-of-state (EOS) and opacities in shock-compressed warm dense matter (WDM), hydrodynamic instabilities and strong magnetic fields
- technology developments for the fast target delivery and laser alignment, testing of innovative diagnostics, control mitigation of the radiation and electromagnetic threats

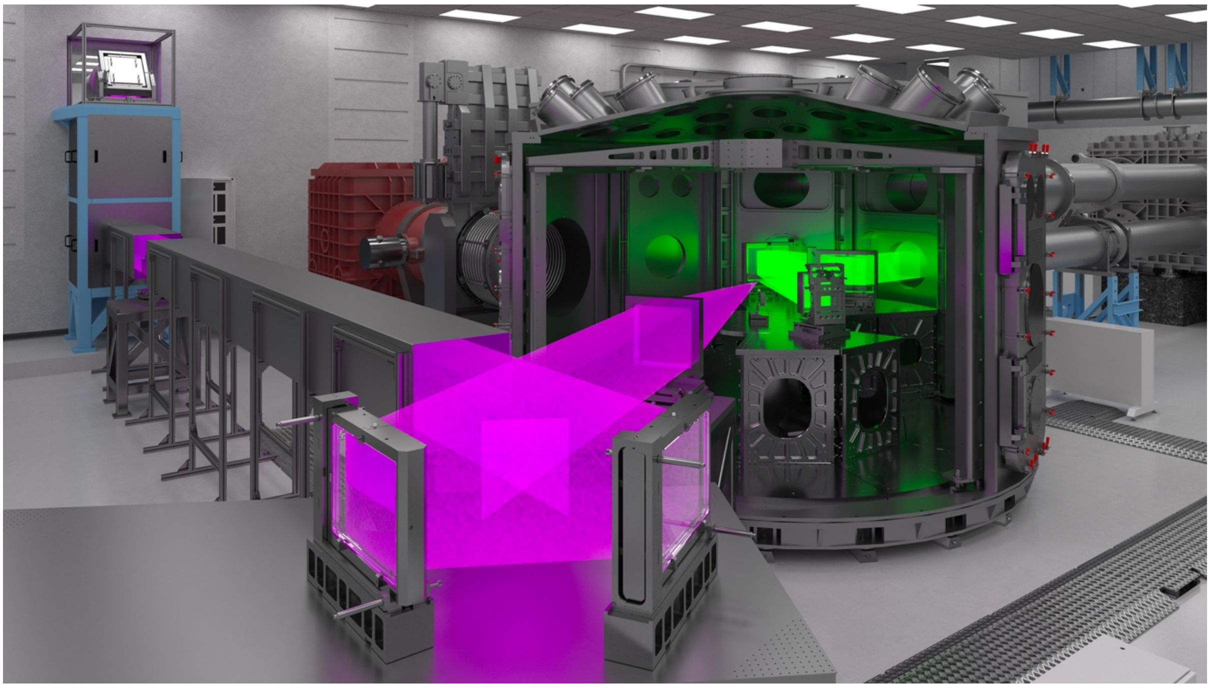

Figure 1: The conceptual layout of the L4n laser ns beamline operating at 527 nm with a few minutes repetition rate (purple) with the L3 backlighter fs laser operating at 820 µm (green) in P3 interaction chamber.

P3 provides a unique platform to investigate fundamental physics processes as well as technology issues of relevance to IFE. The infrastructure constitutes a testbed for the worldwide scientific community interested in the inertial fusion physics, engineering and technology. The host group at ELI-Beamlines, Department 89 will provide:

- technical support for the laser facility operation and data management
- basic laser and plasma diagnostics, target metrology and foam target fabrication
- pulse-power system for generation of strong magnetic fields up to 30 T in the interaction chamber
- logistics, theoretical and numerical support for preparation and analysis of experiments

The L4n laser beamline (kJ/ns) will be commissioned in 1Q 2022 and the synchronized short-pulse backlighter (L3) is expected to be available in 3Q 2022.
The proposed project aims on conducting studies of interest for IFE in collaboration with academic research laboratories and private companies:

- laser facility development
- technology development for high repetition rate target fabrication, alignment and delivery systems
- diagnostics development and LPI experiments

OVERVIEW:

ELI-Beamlines has built and start operating a unique kilojoule, nanosecond high repetition-rate laser system. The beam is converted to 2-omega and transported to the P3 experimental infrastructure. A dedicated platform is being set up for studying various aspects of direct-drive ICF-related physics and technology. The department operating the facility is engaged on several sides:

- Operation of a kJ-ns experimental platform: laser technology testbed support, pulse-power system for strong magnetic field generation
- Theory, numerical developments and simulations of laser plasma interaction, hot electron generation and transport. Fabrication, numerical development and fielding of foam targets for LPI experiments
- Benchmarking of models and numerical tools on high energy laser facilities outside ELI-Beamlines (e.g. PALS, PHELIX etc.)
- Collaborative technology development for high repetition-rate target delivery and alignment systems, mass target production and metrology (solid and foam)

The department already has strong collaborations with American partners (LLE and General Atomics) and European partners (GSI, Focused Energy) in the context of IFE-physics, laser, diagnostics and targetry development.
The ELI-Beamlines facility is an open-access, civilian European research institution, which is in a perfect position to establish links between the IFE activities in USA and Europe. A unique combination of several synchronized laser beams of ns, ps and fs duration in the same chamber and with high repetition rate put ELI-Beamlines in the center of European activities in the field of IFE.

RESEARCH ACTIVITIES IN THE CONTEXT OF THE IFE WHITE PAPER INITIATIVE:

1) **Theory/simulation/experimental activities**
   The department has been very active in the theory and simulation of LPI processes in the underdense plasma and validation of theoretical models in experiments [1-5]. The work in the coming several years will be dedicated to studies of the hydrodynamic and kinetic processes relevant to the direct drive and shock ignition context:
   - laser absorption, multiple beam energy exchange, excitation of parametric instabilities and hot electron control in 2-omega LPI. Numerical simulations will be performed with a PIC code SMILEI in one, two and three spatial dimensions.
   - numerical modeling of homogenization of the foam targets and use foams for studies of hydrodynamic instabilities and strong magnetic field effects. A new model

of the foam homogenization is under development and implementation in a hydrodynamic code FLASH
- development of a pulse power system for strong magnetic field generation and its implementation in the LPI and hydrodynamic experiments

2) Targetry technology

The foam targets are promising for many applications in the direct-drive inertial fusion such as LPI experiments, innovative target designs and bright X-ray radiography sources. However, foam targets present several challenges which need to be addressed in the near future:
- development of a high repetition-rate foam target delivery system. This is necessary for reliable data statistics, avoiding vacuum breaking of large chambers, and exploiting new laser capabilities as much as possible. Existing tape-target technology will be adapted for foam targets [10]
- mass production of foam targets with three different technologies: chemical synthesis, carbon nanotube fabrication and additive manufacturing (3D printing). An example of a 3D printed foam is shown in Fig. 2. These technologies will allow us to produce foams in a broad range of densities from 1 to 100 mg/cc with controlled composition, structural and mechanical properties

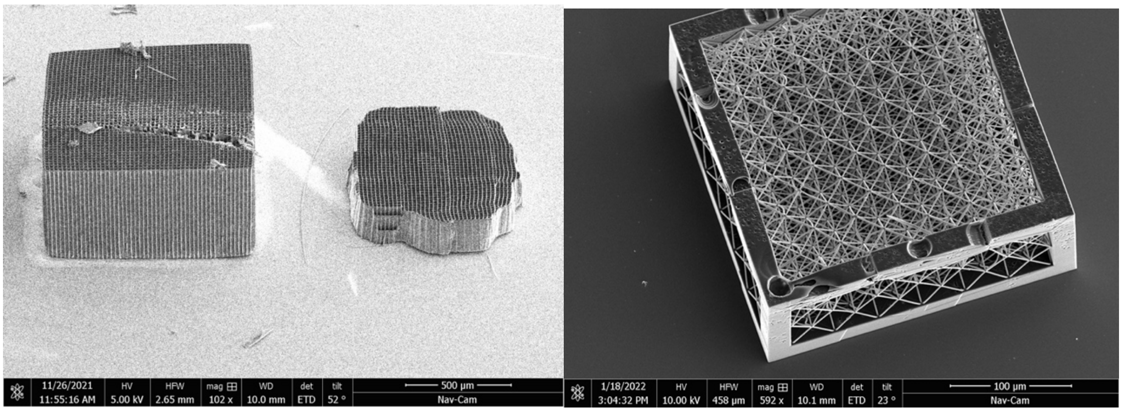

Figure 2: A recent example of a 3D-printed log-pile target (courtesy Institute of Photonics and Electronics, Czech Academy of Sciences).

ELI-Beamlines is following two paths with respect to foam targetry: engaging in international collaborations (academic and industrial) and developing local capabilities.

3) Experimental platform

The experimental chamber P3 [8] of about 50 m^3 is designed as a very versatile platform capable to accommodate up to 4 laser beams. The geometrical layout (Fig. 3 [9]) allows for backlighter operation by using a synchronized fs laser beamline L3 HAPLS (yellow) either in a short-focal length configuration (SFL right panel, for proton or X-ray radiography) or a long-focal length configuration (LFL left panel, for radiography using either wakefield accelerated electrons or betatron radiation in the adjacent chamber (top right corner). The interaction chamber is equipped with a fast target delivery and alignment system, debris protection and diagnostics. The L4n ns interaction beam (green) is coming from the right bottom corner.

The P3 chamber is equipped with a pulsed power device providing the possibility to create a magnetic field in a Helmholtz coil. A steady magnetic field up to 30 T can be created in a ~cm^3 volume and used for LPI experiments (see Fig. 4).

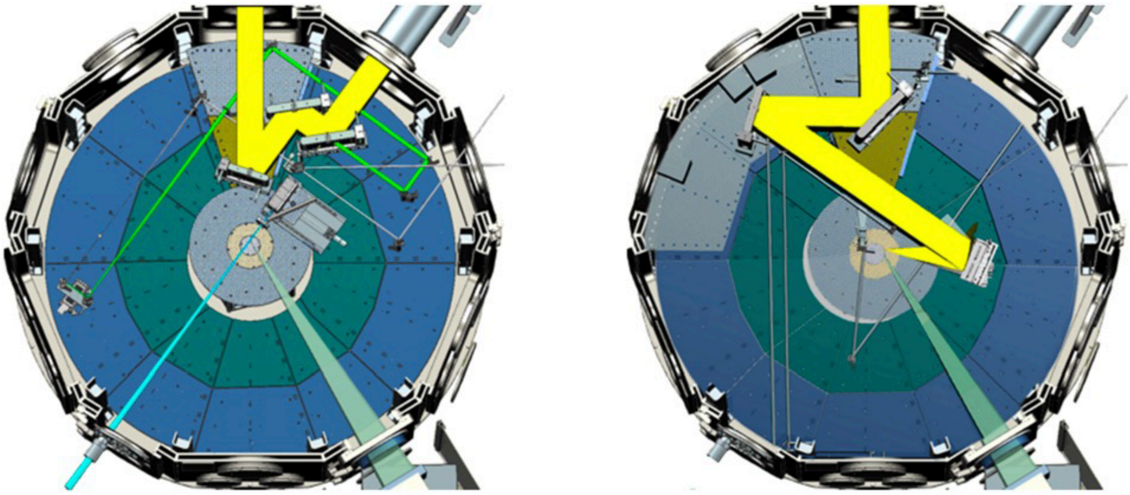

Figure 3: The two multi-beam configurations inside the P3 interaction chamber; the inner diameter of the chamber is about 4.5 m. Left: L4n-L3/LFL and right: L4n-L3/SFL. The L4n beam (green) is entering the chamber from the bottom right corner. The L3 beam (yellow) is entering from the top. The L3 transport system is presented in [7].

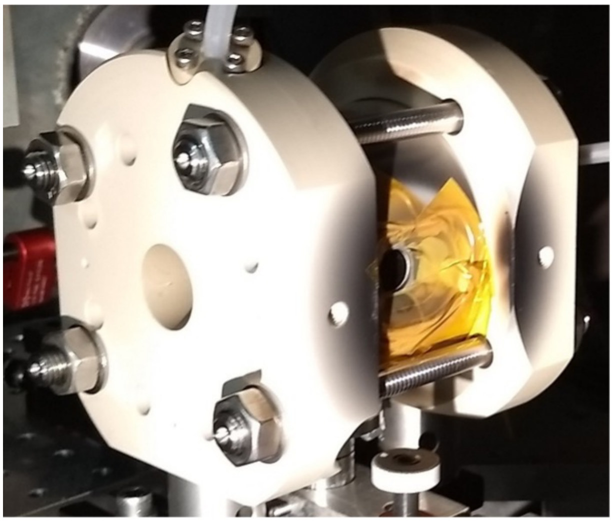

Figure 4: Helmholtz coil developed by and property of HZDR. The pulsed-power device at ELI-Beamlines was optimized for the HZDR coil.

4) Kilojoule, nanosecond high-repetition rate laser & diagnostics

The nominal repetition rate of the L4n laser beamline is one shot per minute, which will considerably will improve data statistics but also presents challenges concerning operation and targetry. The beamline will be initially operated at 2-omega, 527 nm, equipped with a random phase plate and has pulse-shaping capabilities with a step-size of 150 ps in the range of 0.5-10 ns [9]. It is foreseen to develop new frontends to generate broadband spectra and study their effect on LPI. Laser is equipped with a standard set of laser pulse diagnostics. Plasma diagnostics are under development. The first set of diagnostics available in 2022 includes:

- SOP and two-lines VISAR for EoS measurements
- X-ray imagery and spectroscopy in the soft (<2 keV) and hard (~10 keV) range for the plasma temperature and hot electrons detection
- plasma corona interferometry and full aperture backscattering station for measuring Raman and Brillouin processes.

Other plasma diagnostics will be developed on the collaborative basis within this project.

5) **The European context**

ELI Beamlines is a partner of the European ICF community which is launching an action for a new coordinated research project in Europe in the context of IFE [6] aiming on a construction of a common multi-beam laser facility supported by the academic community, industrial partners and a private company Focused Energy [11]. The present project aims to reinforce this initiative by international collaboration with the US partners by a common research of a mutual interest.

KEY METRICS & OPERATIONAL ASPECTS:

The key deliverables for the first 2 years of operation are expected to be the following:
1) Commissioning of the L4n laser system (Q1 & Q2 2022), EoS experiments
2) LPI diagnostic package operational (4Q 2022), LPI experiments
3) Repetition-rate foam target delivery system (Q3 2022), foam homogenization experiments
4) Broadband frontend for L4n (2023), LPI experiments
5) Experiments on hydro instabilities with and without external magnetic field (2023)

Manpower engagement in ELI Beamlines, Department 89 for ICF-IFE research:
- theory & simulation activities ~4 FTE: 3 senior scientists, 2 juniors, 1-2 PhD fellows
- experimental & engineering activities (excluding laser-support personnel) ~3 FTE: 1 senior scientist, 4 juniors, 1 engineer, 1 PhD fellow

Note concerning operation & beamtime at ELI-Beamlines
ELI-BL is operating as a user facility, which provides two principal access modes:
- free of charge academic open-access mode based on scientific merits evaluated by an international selection committee
- payed proprietary access (the cost estimate is under preparation by ELI-ERIC management)

We suggest to establish an American-European academic consortium for studying ICF-related fundamental physics with L4n/P3 and apply for beam time on a multi-annual basis.

RECENT REFERENCES OF RELEVANCE TO THE PROJECT:

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2. Y.J. Gu et al*., Collective absorption of laser radiation in plasma at sub-relativistic intensities,* High Power Laser Sci. Eng**. 7,** e39 (2019)
3. Y.J. Gu et al., *Multi-dimensional kinetic simulations of laser radiation absorption and electron acceleration in inhomogeneous underdense plasma,* Nucl. Fusion **61**, 066014 (2021)
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5. S. Shekhanov et al., *SRS-SBS competition and nonlinear laser energy absorption in a high temperature plasma,* Plasma Phys. Control. Fusion **63**, 115016 (2021)
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7. S. Borneis et al., *Design, installation, and commissioning of the ELI-Beamlines high-power, high-repetition rate HAPLS laser beam transport system to P3*, High Power Laser Sci. Eng. **9**, e30 (2021)
8. S. Weber et al., *P3: An installation for high-energy density plasma physics and ultra-high intensity laser-matter interaction at ELI-Beamlines*, Matter Radiat. Extremes **2**, 149 (2017)
9. N. Jourdain et al., *The L4n laser beamline of the P3-installation: Towards high-repetition rate high-energy density physics at ELI-Beamlines*, Matter Radiat. Extremes **6,** 015401 (2020)
10. F. Condamine et al*., High-repetition rate solid target delivery system for PW-class laser-matter interaction at ELI-Beamlines*, Rev. Sci. Instrum. **92**, 063504 (2021)
11. Focused Energy Inc., https://www.focused-energy.world/